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**Atmospheric corrections of single broadband channel
and multidirectional airborne thermal infrared data.
Application to the ReSeDA Experiment.**

F. Jacob ^{*a,b}, X.F. Gu^a, J.-F. Hanocq^a, N. Tallet^a and F. Baret^a

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^a INRA Climat-Sol-Environnement,
Domaine St Paul, Site Agroparc, 84914 Avignon Cedex 9, France

^b USDA/ARS Hydrology and Remote Sensing Laboratory,
Bldg 007, BARC-West, Beltsville, MD 20705-2350, USA

* Corresponding author :
Phone: (1) 301-504-6142
Fax: (1) 301-504-8931
Email: fjacob@hydrolab.arsusda.gov

Abstract

This study focused on atmospheric corrections of airborne thermal infrared remote sensing data acquired with a multidirectional and single broadband channel sensor during the ReSeDA experiment. For single channel sensors, atmospheric corrections are generally performed using atmospheric radiative transfer models such as MODTRAN 3.5 along with radiosoundings. A sensitivity study was performed using MODTRAN 3.5 simulations to assess the accuracy of the processing regarding to the experimental context. It was shown that the local topography and the atmosphere spatial variability could affect significantly the radiosounding representativeness, whereas the fluctuations of the flight altitude around the nominal value induced non negligible inaccuracies. Moreover, using a broadband sensor induced non linear effects that required a second order correction and further the use of Look Up Tables to reduce computation time. A theoretical error was next proposed accounting for both the sensor accuracy and the experimental uncertainties considered when performing the sensitivity study. This theoretical error was about 1 °C , and agreed well with the results obtained when validating against field measurements.

1 Introduction

Surface temperature is a key variable in the study of the of energy and mass exchanges at the Earth's surface (Choisnel, 1977; Becker and Seguin, 1985). Thermal infrared remote sensing techniques, which allows the mapping of surface temperature, have been recognized very useful for the estimation of surface fluxes (Ottlé and Vidal-Madjar, 1992), including evapotranspiration (Seguin and Itier, 1983; Seguin et al., 1989; Brunet et al., 1991; Seguin et al., 1994) and soil moisture (Carlson et al., 1990). However, radiance measurements in the thermal infrared depend on the wavelength (Kahle and Goetz, 1983; Becker and Li, 1990a; Salisbury and D'Aria, 1992; Humes et al., 1994; Barducci and Pippi, 1996), the view zenith angle (Kimes and Kichner, 1983; Prévot et al., 1993; Lagouarde et al., 1995), the time and sun position (Lagouarde and Olioso, 1995; Seguin et al., 1999), and the spatial scale (Becker and Raffy, 1987; Becker and Li, 1995; Seguin et al., 1999). Moreover, remotely sensed data are influenced by the atmosphere, especially by the absorption and emission effects induced by water vapor, carbon dioxide and ozone (Chandrasekhar, 1960; Lenoble, 1989). These atmospheric effects can lead to a temperature difference between the surface and the sensor larger than 10 °C (Cooper and Asrar, 1989; Wukelic et al., 1989).

Several methods have been proposed over the two last decades to remove these atmospheric effects, depending on sensor spectral and directional characteristics (Maul, 1983; Singh, 1984; Malkevich and Gorodetsky, 1988). The most successful

method is the split window algorithm for multispectral sensors (Price, 1984; McClain et al., 1985; Becker and Li, 1990b, 1995; François and Ottlé, 1996; Caselles et al., 1997) although some inaccuracies still remain, due to the spectral variation of surface emissivity which is generally unknown. Data acquired with single channel and multidirectional sensors can be corrected from atmospheric effects using the multiangular approach. Nevertheless, such a method does not provide good results over land surfaces because of the non Lambertian behavior of such surfaces. In this context, the alternative solution consists in using an atmospheric radiative transfer model along with radiosoundings (Schott and Chédin, 1985; Kneizys et al., 1983; Susskind et al., 1984; Djavadjji and Anderson, 1987; Perry and Moran, 1994).

The airborne thermal infrared sensor used during the ReSeDA (**R**emote **S**ensing **D**ata **A**ssimilation) experimental phase was a single channel multidirectional sensor. The ReSeDA project aimed at developing the synergistic use of multispectral, multiangular and multitemporal remote sensing data for both agricultural surface characterization and assimilation into SVAT (Soil - Vegetation - Atmosphere Transfer) and crop functioning models (Prévot et al., 1998; Oliso et al., 1998, 2001). This should provide a better understanding and evaluation of soil and vegetation functioning (biomass production, crop yield, energy balance and water budget). In the framework of this experiment, collecting and preprocessing airborne thermal infrared measurements aimed at providing high spatial resolution data to first characterize the spatial variability inside agricultural fields and second study upscaling

effects. In this context, the goal was to generate a surface temperature data set with an accuracy about 0.8 °C (Seguin et al., 1999).

The objective of this study was to perform and assess both the instrumental and atmospheric corrections of the airborne thermal infrared measurements acquired during the ReSeDA experiment. The main part was focused on the atmospheric corrections that were performed using the atmospheric radiative transfer model MODTRAN 3.5 along with radiosoundings. In a first time, we present the data acquisition and instrumental preprocessing. In a second time, we analyse the results we obtained when assessing the consequences of the experimental inaccuracies, i.e. the use of a non coincident radiosounding and the fluctuations of flight altitude around the nominal values. Next, we present the method we developed to perform atmospheric corrections when considering a broadband sensor that induced non linear effects. Then, we assess the theoretical accuracy of the method accounting for the experimental inaccuracies. Finally, the remote sensing estimates are validated against field measurements.

2 Data acquisition and MODTRAN 3.5 simulations

The ReSeDA experiment took place in the south east of France, close to Avignon, at the north of the Alpilles mountain chain (N 43 ° 47 ' latitude, E 4 ° 45 ' longitude, 10 m altitude above sea level). The area was a 5 × 5 km² Mediterranean agricultural region, with sunflower, wheat, corn, grassland and alfalfa fields about

$200 \times 200 \text{ m}^2$ size. During the experiment that lasted from December 1996 up to December 1997, three kinds of surface temperature datasets were collected. Satellite data (METEOSAT, NOAA / AVHRR, Landsat) were available with respect to satellite orbits and meteorological conditions. Airborne measurements were carried out steadily every 15 days using an INFRAMETRICS 760 thermal infrared video camera, and occasionally using DAIS and MAIS sensors. Field data were acquired routinely using HEINMANN radiometers and occasionally using EVEREST radiometers. In this study, we focused on INFRAMETRICS 760 airborne data and EVEREST ground based measurements.

2.1 Airborne data

The INFRAMETRICS 760 thermal infrared video was set aboard a PIPER PA28 ARROW4 plane that flew approximately one or two times per month on clear sky days from January, 30 to September, 18, 1997. Flight nominal altitude was set to 1500 m and 3000 m using a Global Positioning System (GPS), which yielded nadir spatial resolutions of 10 m and 20 m respectively. Four flight lines were parallel to the principal plane and one was perpendicular. The five lines and 2 altitudes were completed within 1.5 hour centered around solar noon. To minimize radiometric noise, the sensor was setup with a broadband filter that ranged from 7.25 to $13.25 \mu\text{m}$ (see figure 1). The multidirectional observations were achieved using a 80° large Field Of View (FOV) lens. The targets were scanned by a two oscillating mirror system that projected the beam on a HgCdTe detector cooled

at -200 °C by a Stirling system. The scanning system provided 230×376 pixel images. The radiometric resolution was about 0.2 °C and 0.4 °C for brightness temperature ranges of 20 °C and 50 °C respectively. The radiance detected over the [7.25 - 13.25] μm spectral interval was expressed in brightness temperature assuming a target emissivity of 1. The data were collected on a video tape with a 25 Hz frequency, and numerized with a 1 Hz frequency (1 image every 25).

[Figure 1 about here.]

To verify and eventually improve the sensor accuracy, a laboratory calibration was performed in a air conditioned room using a blackbody. Ambient and blackbody temperatures were set between 15 and 35 °C with a 10 °C step, and between 15 and 55 °C with a 10 °C step respectively. With one set of ambient and blackbody temperatures, the measured temperature was recorded during 3 hours on a video tape. Simultaneously, the sensor internal temperature was measured at the base of the lens and printed every 24 images (instrumental feature). Data analysis showed a temperature overestimation when the internal temperature was larger than the target one, and an underestimation in the opposite case. These differences were explained by the absorption and reemission effects induced by the lens. Therefore, a second order polynomial was calibrated to estimate the target brightness temperature from the measured temperature accounting for the sensor internal temperature. Results presented a Gaussian calibration residue distribution (difference between sensor and reference temperatures) with a mean value of 0 °C

and a standard deviation of 0.23 °C.

The 80 ° FOV used to perform multidirectional observations induced important geometric distortions as well as an angular variation of the directional radiometric sensitivity. To remove the geometrical distortions, a 3rd degree polynomial was calibrated over images acquired when aiming at a regular mesh-grid in laboratory. The correction residue was lower than 1.5 pixel. The optical center was simultaneously located to estimate further the view zenith angle of each pixel from the distance between a given pixel and the optical center. This distance was calculated accounting for the geometrical distortions since considering or not these distortions induced differences up to 6 ° for large view zenith angles. It will be shown further that such an inaccuracy could induce significant errors when performing the atmospheric corrections. The sensor directional sensitivity was characterized by observing an homogeneous water surface. The sensor - target system was radiometrically isolated and in thermal equilibrium with its environment. The water angular emissivity variation was assumed to be negligible between 0 ° and 40 ° (Rees and James, 1991). Data analysis showed a significant noise on image borders. The shape of the radiometric response had a 0.8 ° dynamics and did not present a simple pattern allowing a polynomial fitting. Therefore, an image of temperature difference between each pixel and the optical center was generated.

2.2 Radiosoundings and *in-situ* measurements

The radiosoundings used to perform atmospheric corrections were launched around solar noon by the METEO FRANCE meteorological station close to the Nîmes airport. This station was located 30 km towards the west of the experimental site, and its altitude was about 60 m above sea level. The radiosoundings provided profiles of atmospheric pressure, temperature and humidity. Measurement levels corresponded to a step of 250 mbar pressure decreasing, and to characteristic points representing an inversion of temperature or humidity. This induced approximately 30 levels of measurements between 0 and 10 km. Additionally, radiosoundings were launched by METEO France team of Toulouse at 12H00 U.T. from the experimental site during three days in 1997 (April, 16; April, 18; June, 12).

Field data were acquired simultaneously with airborne observations during 5 days between August, 7 and September, 18. The instrument used was an Everest Inter Science manual infrared thermometer AGRI-THERM 112ALCS, which measured target brightness temperature from the incoming radiance over the [8 - 14] μm spectral band (close to that of airborne sensor). The lens FOV was about 4 °. Measurements were performed with a nadir viewing at 1 m height, which provided a 10 cm diameter circular footprint. Each field was exhaustively sampled using a 20 m grid pattern. The considered fields corresponded to alfalfa, grassland, sunflower and bare soils, and exhibited brightness temperatures ranging from 25 °C to 45 °C. Two water surfaces with known temperatures (one cold and one hot) were

used as reference targets for calibration. To get a better accuracy, this calibration was repeated every 25 measurements, providing a daily calibration (Verbrughe and Guyot, 1992). The RMSE (Root Mean Square Error) between calibration data and daily linear regressions was about 0.6 °C.

2.3 MODTRAN 3.5 model use

The atmospheric corrections were performed using MODTRAN 3.5 code (Berk et al., 1998) along with radiosoundings. CO_2 mixing ratio was set to 360 ppmv, and aerosol optical thickness in boundary layer to a visibility of 23 km. The other atmospheric components were provided by MODTRAN 3.5 climatological data bank for mid-latitudes. Surface emissivity was assumed to be equal to unity over the [7.25 - 13.25] μm spectral range, which induced to consider a surface brightness temperature. This choice was driven by the variability of the natural surface apparent emissivity, which was not actually well characterized. To perform a sensitivity study regarding to the experimental context, a database was simulated using MODTRAN 3.5. For a given radiosounding and a given flight altitude, the brightness temperature at the sensor level was simulated for a range of surface brightness temperature between -10 °C and 60 °C with a 10 °C step; and a range of view zenith angle between 0 ° to 50 ° with a 5 ° step. The choice of the surface brightness temperature range was driven by the multitemporal characteristic of the IN-FRAMETRICS 760 data base that included winter and summer observations. The choice of the zenith view angle range was driven by the FOV of the lens used with

the INFRAMETRICS 760. For a given sensor relative altitude H and a given view zenith angle θ , MODTRAN 3.5 simulated spectral radiances were integrated over the sensor broadband and normalized to compute the Equivalent Spectral Radiance ESR (Leroy, 1992; Barducci and Pippi, 1996):

$$ESR(Tb) = \frac{\int_{7.25\mu m}^{13.25\mu m} L_{BB}(\lambda, Tb) S(\lambda) d\lambda}{\int_{7.25\mu m}^{13.25\mu m} S(\lambda) d\lambda} \quad (1)$$

where Tb is the brightness temperature deduced from the radiance using a polynomial regression with an accuracy of 0.01 °C. In this way, the atmospheric radiative transfer equation could be rewritten as:

$$\begin{aligned} ESR(Tb_{I760}(\theta, H)) &= ES\tau(Tb_{surf}, \theta, H) ESR(Tb_{surf}) \\ &+ ESR(Tb_{atmos}(\theta, H)) \end{aligned} \quad (2)$$

where Tb_{surf} is the surface brightness temperature, Tb_{I760} is the brightness temperature at the sensor level, Tb_{atmos} is the atmospheric brightness temperature at the top of the atmospheric layer between the surface and the sensor, and $ES\tau$ is the Atmospheric Equivalent Spectral Transmittance of this layer:

$$ES\tau(Tb_{surf}, \theta, H) = \frac{\int_{7.25\mu m}^{13.25\mu m} L_{BB}(\lambda, Tb_{surf}) \tau_a(\lambda, \theta, H) S(\lambda) d\lambda}{\int_{7.25\mu m}^{13.25\mu m} L_{BB}(\lambda, Tb_{surf}) S(\lambda) d\lambda} \quad (3)$$

The database was simulated such as we could next perform a sensitivity study regarding to the experimental context, which means considering the impact of both the atmosphere spatial variability and the topography on the representativeness of

non spatially coincident radiosoundings, as well as the consequences of the fluctuations of the sensor altitude around the nominal value. More details about this simulated data base are given in the next section that presents the results we obtained when performing the sensitivity study.

3 Analysis of atmospheric effects on single channel and multidirectional airborne thermal infrared images

Figure 2 displays the evolution of the difference $\Delta T = Tb_{I760} - Tb_{surf}$ as a function of Tb_{surf} when considering two extreme cases, i.e. a wet atmosphere with a water vapor content W about 2.39 g.cm^{-2} and a dry atmosphere with a W about 0.62 g.cm^{-2} . The results showed that the difference $\Delta T = Tb_{I760} - Tb_{surf}$ depended on Tb_{surf} , W and air temperature Ta . This could be explained by the balance between atmospheric absorption (characterized by transmission) and atmospheric emission, the absorption term being weighted by Tb_{surf} (Eq. 2). Therefore, cold surfaces enhanced emission, which induced an overestimation of Tb_{surf} ; whereas hot surfaces enhanced absorption, which induced an underestimation. At the neutral point where atmosphere has not effect, absorption and emission were equal and canceled out. The value of this point depended on temperature and water vapor profiles of the atmospheric layer, and was independent of view zenith angle (figure not shown). The difference $\Delta T = Tb_{I760} - Tb_{surf}$ increased as W increased, but also as view zenith angle θ increased since optical path was larger (figures 3 & 4). For the wettest atmosphere, the angular variation induced atmo-

spheric effects within -4.5°C to 2.7°C with a variation up to 0.9°C for a θ varying from 40° to 45° and a Tb_{surf} about 50°C . These large effects justified the efforts directed to accurately estimate the view zenith angle when characterizing the sensor (section 2).

[Figure 2 about here.]

[Figure 3 about here.]

[Figure 4 about here.]

As mentioned previously, the radiosoundings used were launched from the METEO-FRANCE station of Nîmes that was 60 m above sea level whereas the experimental site was about 10 m above sea level. To assess the consequences of this difference on the representativeness of the radiosoundings, we compared two databases simulated using "raw" and "hybrid" radiosoundings. "Raw" radiosoundings corresponded to those provided by METEO FRANCE station. "Hybrid" radiosoundings were generated using the following procedure (figure 5). Since lowest atmosphere layers are strongly affected by the underlying land surfaces, the atmosphere between 10 and 160 m (100 m above METEO France station) was characterized using measurements of air pressure, temperature and humidity collected at the meteorological station of the ReSeDA site (2 m above the surface). Assuming the horizontal advection increases with altitude and induces an homogenization at the blending height (Mason, 1988), the atmosphere above 160 m was

described using Nîmes radiosounding. The largest difference between brightness temperatures at the sensor level simulated from "raw" and "hybrid" radiosoundings was obtained on May, 15 with a sensor altitude of 1500 m. The altitude was explained by the larger contribution of the lowest layers in the atmospheric radiative transfer between ground and sensor levels when considering a 1500 m altitude instead of 3000m. The day corresponded to the greatest relative variation of W (10 %) combined with a large air temperature (27 °C). Figure 6 displays for this case the evolution of the difference $\Delta T = Tb_{raw} - Tb_{hyb}$ as a function of Tb_{surf} , where Tb_{raw} and Tb_{hyb} are the brightness temperatures at the sensor level simulated using the "raw" and "hybrid" radiosoundings respectively. Tb_{raw} was lower and larger than Tb_{hyb} for cold and hot surfaces respectively, whereas this trend was emphasized as the view zenith angle increased. This could be explained considering previous observations related to Figure 2 where it was shown that atmospheric effects induced an overestimation of low surface brightness temperatures and an underestimation of large ones. This trend was emphasized when using "hybrid" radiosoundings since it consisted in adding a 50 m thickness layer at the bottom of atmosphere and therefore in increasing the atmospheric water vapor content W . The whole set of simulations showed the same phenomenon, with a global RMSE (Root Mean Square Error) between simulations from "raw" and "hybrid" radiosoundings about 0.25 °C. These results demonstrated that topography could have a significant influence on radiosounding representativeness. However, it was

difficult to conclude quantitatively since the "hybrid" radiosoundings were generated considering a blending height about 100 m, which was an strong assumption since this specific height can vary from 100 to 250 m according to the boundary layer conditions.

[Figure 5 about here.]

[Figure 6 about here.]

The results we obtained when assessing the influence of the atmosphere spatial variability on the radiosounding representativeness could be explained in a similar way. We were able to perform the comparison between simulated brightness temperatures at the sensor level for three days when radiosoundings were launched from the experimental site. In this case, we used the "hybrid" radiosoundings for the comparison to consider atmospheric layers having the same thickness. The comparison results were significantly different from a day to another. RMSE was low for April, 16 and April, 18 (about 0.2 °C), whereas it increased up to 0.7 °C for June, 12. The largest difference corresponded to the largest relative variation of W (12 %) combined with a large air temperature about 29 °C. Figure 7 displays for this case the evolution of the difference $\Delta T = Tb_{hyb} - Tb_{ins}$ as a function of Tb_{surf} , where Tb_{hyb} and Tb_{ins} are the brightness temperatures at the sensor level simulated using the "hybrid" and *in-situ* radiosoundings respectively. As mentioned in the previous paragraph, the atmosphere model having the larger W

(*in-situ* radiosounding here) induced more important over- and underestimations over cold and hot surfaces respectively. However, the small number of *in-situ* radiosoundings did not allow to draw a general conclusion. We only could state say that the spatial variability of the atmosphere may induce significant differences in some cases.

[Figure 7 about here.]

The impact of the fluctuations of the flight altitude around the nominal value was assessed performing MODTRAN 3.5 simulations for a range of altitude. Figures 8 and 9 display the evolution of the brightness temperature at the sensor level as a function of the relative altitude H defined by $H = z - z_s$ where z and z_s are the altitudes above sea level of the sensor and the surface respectively. We noticed that this evolution depended on the altitude itself, the surface brightness temperature and the view zenith angle. This was induced by the variation with the altitude of the balance between atmospheric absorption and emission. This balance variation could be explained considering the observations of Perry and Moran (1994). First, atmospheric transmittance (related to absorption) decreases with altitude (negative derivative) between 0 and 10 km (above 10 km, there is no water vapor). Second, atmospheric emission increases with altitude (positive derivative) between 0 and 3 km, and remains constant above. Then, let us consider the derivative of atmospheric radiative transfer equation (Eq. 2) with respect to the relative altitude.

$$\begin{aligned}
\frac{\partial ESR(Tb_{I760}(\theta, H))}{\partial H} &= ESR(Tb_{surf}) \frac{\partial E\tau(Tb_{surf}, \theta, H)}{\partial H} \\
&+ \frac{\partial ESR(Tb_{Atmos}, (\theta, H))}{\partial H}
\end{aligned} \tag{4}$$

Eq. 4 shows that the derivative of brightness temperature at the sensor level with respect to altitude could be positive or negative according to the relative altitude and surface brightness temperature. Low surface brightness temperatures emphasized the derivative of the emission term that is positive between 0 and 3 km and null above. Large surface brightness temperatures emphasized the derivative of the absorption term that is negative regardless to the altitude. Therefore, low surface brightness temperatures induced an increase of the sensor brightness temperature as the altitude increased between 0 and 3 km and a decrease above; whereas large surface brightness temperatures induced a decrease of the sensor brightness temperature as the altitude increased with a more important decrease for larger temperatures. Obviously, these behaviors were emphasized at larger view zenith angles since the optical thickness was larger. Moreover, the variation was more important at lower altitudes since the addition of an atmospheric layer induced more important effects. The dynamics could reach up to 0.2 °C/100m at a 1500 m altitude, for a 50 ° view zenith angle and a 60 °C surface brightness temperature. These results were important since the flight altitude values provided by the GPS fluctuated about ± 100 m around the nominal values.

[Figure 8 about here.]

[Figure 9 about here.]

4 Routine atmospheric corrections of broadband and multidirectional thermal infrared data

The common way to perform atmospheric corrections when using atmospheric radiative transfer is to invert the atmospheric radiative transfer equation (Eq. 2) in order to express the outgoing surface radiance from the at sensor radiance (Schmugge et al., 1998). This approach assumes that the radiances are linearly related. However, Eq. 3 shows that the atmospheric equivalent spectral transmittance depends on the surface temperature, which could induce some non linear effects especially when considering a broadband filter such as that used with the INFRA-METRICS 760 during the ReSeDA experiment (ranging from 7.25 to 13.25 μm). Therefore, we assessed these non linear effects by estimating the accuracies of first and second order regressions between radiances at the surface and sensor levels. When considering a linear regression, the resulting RMSE between simulations and regressions after conversion in temperature was about 0.25 $^{\circ}\text{C}$ with a maximum difference about 0.4 $^{\circ}\text{C}$. On the other hand, the RMSE was about 0.025 $^{\circ}\text{C}$ when considering a second order regression. Since one of the goals of this study was to reach an accuracy of 0.8 $^{\circ}\text{C}$ for surface temperature as mentioned in the introduction, we decided to use a second order polynomial regression when ex-

pressing radiance at the sensor level from surface radiance:

$$\begin{aligned} ESR(Tb_{I760}(\theta, H)) &= \alpha(\theta, H) ESR^2(Tb_{surf}) \\ &+ \beta(\theta, H) ESR(Tb_{surf}) + \gamma(\theta, H) \end{aligned} \quad (5)$$

When performing atmospheric corrections for multidirectional observations, a simple way to significantly reduce computation time is to express the atmospheric transmittance and upwelling radiance as linear functions of both the secant of view zenith angle and water vapor content (Becker, 1987). Moreover, using a second order regression required to consider also the non linear term $\alpha(\theta, H)$ that corresponded mainly to the coupling of surface, atmospheric and instrumental effects. Since it was not easy to model the angular variation of this coefficient (figure 10), we considered an average value $\bar{\alpha}(H)$ over the $[0 - 50]^\circ$ angular domain. The second term $\beta(\theta, H)$ corresponded to the atmospheric transmittance of the layer between surface and sensor, while the third term $\gamma(\theta, H)$ corresponded to the upwelling atmospheric emission. Therefore, these two coefficients could be written as linear functions of the secant of the view zenith angle θ :

$$\beta(\theta, H) = \frac{D_1(H)}{\cos \theta} + D_2(H) \quad (6)$$

$$\gamma(\theta, H) = \frac{E_1(H)}{\cos \theta} + E_2(H) \quad (7)$$

Coefficients $\bar{\alpha}(H)$, $D_1(H)$, $D_2(H)$, $E_1(H)$, $E_2(H)$, were calibrated over MODTRAN 3.5 simulations. The largest error on the linearization of $\beta(\theta, H)$ and $\alpha(\theta, H)$ coefficients corresponded to the atmosphere having the largest atmospheric

water vapor content W . This was in agreement with previous observations reported by Becker (1987) who noticed a decrease of the linearization accuracy with an increase of W . For this worst case, the relative uncertainties on the three coefficients were 14 % for $\alpha(\theta, H)$, 0.3 % for $\beta(\theta, H)$, and 0.3 % for $\gamma(\theta, H)$ (figure 10). Strong scattering on $\alpha(\theta, H)$ had no consequence on the temperature estimation error because its contribution to the signal was low: about 0.5 % for low temperatures and 1.5 % for high temperatures (figure 11). To evaluate the accuracy of this approach, 3000 simulations were performed by randomly drawing view zenith angle values within the $[0 - 50]^\circ$ domain and surface brightness temperature values within the $[-10 - 60]^\circ\text{C}$ domain. The distribution of the difference in brightness temperature at the sensor level between MODTRAN 3.5 simulations and the regression was a Gaussian with a mean value of 0°C and a standard deviation of 0.025°C .

[Figure 10 about here.]

[Figure 11 about here.]

The second order regression we used induced that instead of inverting Eq. 2, we had to resolve the following second order equation:

$$\begin{aligned}
& \bar{\alpha}(H) ESR^2(Tb_{surf}) \\
& + \left(\frac{D_1(H)}{\cos \theta} + D_2(H) \right) ESR(Tb_{surf}) \\
& + \left(\frac{E_1(H)}{\cos \theta} + E_2(H) - ESR(Tb_{I760}) \right) = 0
\end{aligned} \tag{8}$$

Since this second order equation resolution was time consuming, we decided to use Look Up Tables when performing the atmospheric corrections in an operational way. Each Look Up Table corresponded to a set of radiosounding and a flight altitude, with a resolution of 0.1 °C in brightness temperature at the sensor level and 0.1 ° in view zenith angle (figure 12). For each cell of a LUT, surface brightness temperature was estimated from the brightness temperature at the sensor level solving equation 8. The function $f(ESR(Tb_{surf})) = 0$ in equation 8 was concave (figure not shown). As the ESR incoming at the sensor level increased with the ESR outgoing from surface, the solution considered for the surface brightness temperature was the lowest one. These LUT were computed using radiosoundings provided by METEO FRANCE station of Nîmes. This choice was driven by the fact that the way we computed hybrid radiosoundings was open to criticism as discussed previously.

[Figure 12 about here.]

5 Accuracy assessment and validation

We next assessed the theoretical accuracy of the whole processing considering each step uncertainty. As mentioned in section 2, the accuracy of the instrumental calibration was about 0.5 °C when considering the residual error of sensor calibration. The accuracy of the atmospheric correction was next estimated accounting for the consequences of the several atmospheric effects discussed in section 3. The im-

pact of each effect on Look Up Table accuracy was estimated using equation 8 in which was injected different sets of coefficients $\bar{\alpha}$, D_1 , D_2 , E_1 , E_2 , corresponding to different situations, i.e. different radiosoundings or different altitude levels (figure 13). The uncertainty was quantified by computing the RMSE between retrieved surface brightness temperature. This RMSE was about 0.35 °C between results from "raw" and "hybrid" radiosoundings, about 0.45 °C between results from Nîmes and *in-situ* radiosoundings, and about 0.35 °C when considering altitude fluctuations (± 100 m). Uncertainties due to flight altitude fluctuations and topography effects were calculated considering each day of the experiment. However, this was not possible when assessing the impact of the atmosphere spatial variability since radiosoundings launched from the experimental site were available for three days only. Moreover, we observed that this aspect could be very important. In this context, the proposed accuracy had to be considered with many care. It was quantified using a quadratic summation of each step uncertainty, from instrumental to atmospheric corrections. This yielded a value close to 1 °C.

[Figure 13 about here.]

The final step of this study consisted in validating INFRAMETRICS 760 airborne data against EVEREST field measurements acquired during 5 days of the experiment. The data set used was reduced considering only field and airborne measurements that were temporally and spatially coincident. This yielded to perform 3 comparisons over bare soil (flight altitude of 3000 m on September, 4),

alfalfa crop (flight altitude of 1500 m on September, 9) and grassland (flight altitude of 1500 m on September, 18). To avoid border effects, the data selected inside airborne images were located at the centers of the fields and corresponded to squares of 25 pixels for a 3000 m altitude and to squares of 100 pixels for a 1500 m altitude. As field measurements were performed with a nadir viewing, airborne data were selected such as view zenith angle was lower than 10° . Results showed that bare soil brightness temperatures measured in the field expressed a large dynamics, about 5°C (figure 14), which could be explained by local roughness inducing shadow effects. The difference in surface brightness temperature between the field measurements and the estimations from airborne data after instrumental and atmospheric corrections was about 1°C . This was acceptable, considering the importance of atmospheric corrections (about 10°C , due to large surface brightness temperatures). For alfalfa field, a difference of 0.5°C was observed between the field measurements and the airborne estimations. Grassland showed an interesting feature: only one part of the field was harvested, inducing a large contrast between the two parts (figure 15). Histograms of field and airborne surface brightness temperatures presented two modes corresponding to the two parts of the field. In this case, comparison showed also a difference of 1°C . Finally, we could conclude that this partial validation over three fields was consistent with the theoretical budget since we noticed some differences around 1°C .

[Figure 14 about here.]

[Figure 15 about here.]

6 Conclusions

This study dealt with atmospheric corrections of airborne multidirectional thermal infrared remote sensing data acquired during the ReSeDA experiment. These corrections were performed using the MODTRAN 3.5 radiative transfer code along with radiosoundings since the data were collected using a single channel sensor. A data base was simulated to assess the consequences of the experimental context on the processing accuracy. It was shown that the local topography, the spatial variability of the atmosphere and the fluctuations of the flight altitude around the nominal value induced significant uncertainties. The influences of CO_2 mixing ratio and aerosol optical thickness for boundary layer were also evaluated but results showed negligible effects, which was explained by the use of a broadband sensor. Considering the uncertainties of each data processing step, i.e instrumental and atmospheric corrections, we proposed an accuracy about 1 °C. Nevertheless, this theoretical value had to be consider with many care for three reasons. First, the approach used to estimate the effects induced by the topography was based on strong assumptions that were open to criticism. Second, the impact of the atmospheric variability was quantified for three days of the experiment only. Third, the temporal dynamics of the atmosphere was not investigated. Indeed, the radiosoundings were launched around 12H00 U.T., while airborne observations were performed

during one hour around solar noon, which might induce an additional source of uncertainty since the boundary layer characteristics change during this period of the day.

The simulated data base allowed next to assess the possible non linear atmospheric effects induced by the use of a broadband sensor. It was shown that these effects could be significant as compared to the accuracy we tried to reach in the framework of the ReSeDA experiment. Therefore, we used a second order regression to express the radiance at the sensor level from the surface radiance. This required next the use of atmospheric Look Up Tables to significantly reduce computation time when performing atmospheric corrections in an operational way. The validation was performed over a small data set including a limited number of cases. The comparison between the airborne data and the field measurements demonstrated clearly the importance of the corrections and their performances. The differences between measured and retrieved surface brightness temperature was about 1 °C, in good agreement with the theoretical error budget. However, significant differences may occur because of the impact of the atmosphere spatial variability that was not well quantified. It was interesting to notice that the high spatial resolution airborne data depicted a spatial variability similar to that of field measurements and can constitute therefore an interesting data set when studying scaling effects. It would be interesting to extend in the future the validation on a larger number of cases. In the framework of the ReSeDA experiment, other field measurements

were acquired routinely. These data were local and therefore not representative of the field variability, but they can be used to validate the atmospheric corrections for each day of airborne acquisition and therefore for a important range of surface brightness temperature.

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